II. Potvrda naboja boje

ELEKTRODINAMIKOM DO "BOJE" KAO NABOJA JAKE SILE

- **PRAGOVI PRODUKCIJE HADRONA**
  (boja kao globalni naboj)
- **3. HADRONSKI MLAZ**
  (boja kao globalni naboj)
- *SU(3)-boje i 8 OBOJENIH GLUONA*

SONDIRANJE DIRACOVIH EL. ČESTICA

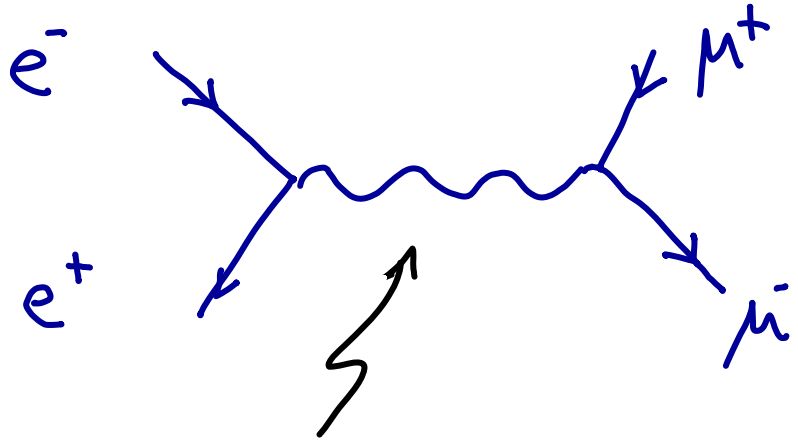
- REZOLUCIJA PREMA RELACIJAMA NEODREĐENOSTI

$$\Delta x c \, \Delta p \gtrsim \hbar c$$

d $\sqrt{q^2}$ 0.2 GeV fm

PRIJENOS 4-IMP. $\sqrt{q^2}$	REZOLUCIJA d
0.2 GeV	$1\,\text{fm} = 10^{-15}\,\text{m}$
5 GeV	$4 \cdot 10^{-17}\,\text{m}$
5 TeV	$4 \cdot 10^{-20}\,\text{m}$

MJERENJE ENERGIJSKE OVISNOSTI ANIHILACIJE



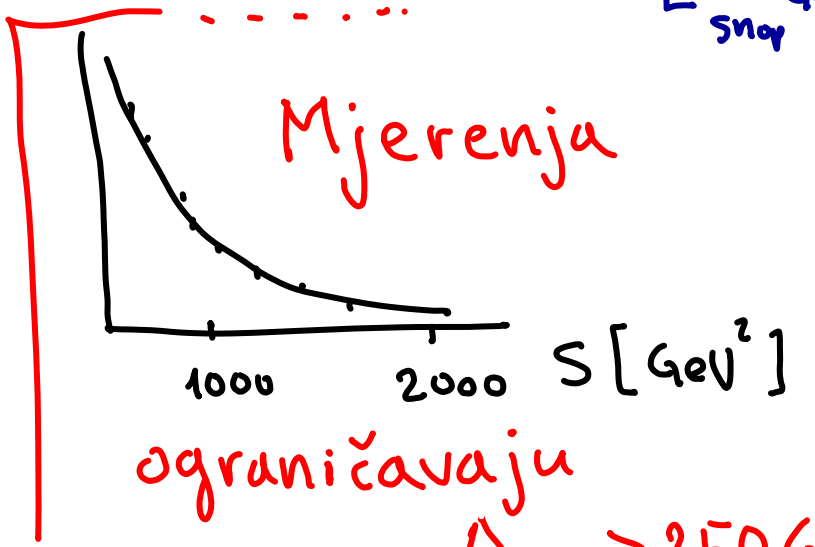
$$\frac{1}{q^2} \to \frac{1}{q^2}\left(1 + aq^2 + bq^4 + \cdots\right)$$

dalo bi

$$\sigma \to \frac{4\pi\alpha^2}{3s} F$$

$$F = 1 + as = 1 \pm \frac{s}{\Lambda_\pm^2}$$

$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s} \simeq \frac{22\,\text{nb}}{E^2_{\text{snop}}\,(\text{GeV}^2)}$$



ograničavaju

$$\Lambda_\pm > 250\,\text{GeV}$$

$$\Rightarrow d < \frac{0.2}{250}\,\text{fm} \simeq 10^{-3}\,\text{fm}$$

KRATKA POVIJEST "BOJE"

- DODATNI STUPANJ SLOBODE POTREBAN ZA Δ^{++} i Ω^{-}
- Omjer "R" anihilacije u hadrone
- Schwingerovo predviđanje da

"implicitni stupnjevi slobode (Greenbergovog parakvarkovskog modela) moraju imati dinamičku ulogu (p.12 u hep-ph/0212174)

BOJNI FAKTORI PRI SUDARIMA ELEKTRONA I POZITRONA

Colour is conserved and quarks are produced as $r\bar{r}$, $g\bar{g}$, $b\bar{b}$
For a single quark flavour and single colour

$$\sigma(e^+e^- \to q_i\bar{q}_i) = \frac{4\pi\alpha^2}{3s}Q_q^2$$

- Experimentally observe jets of hadrons:

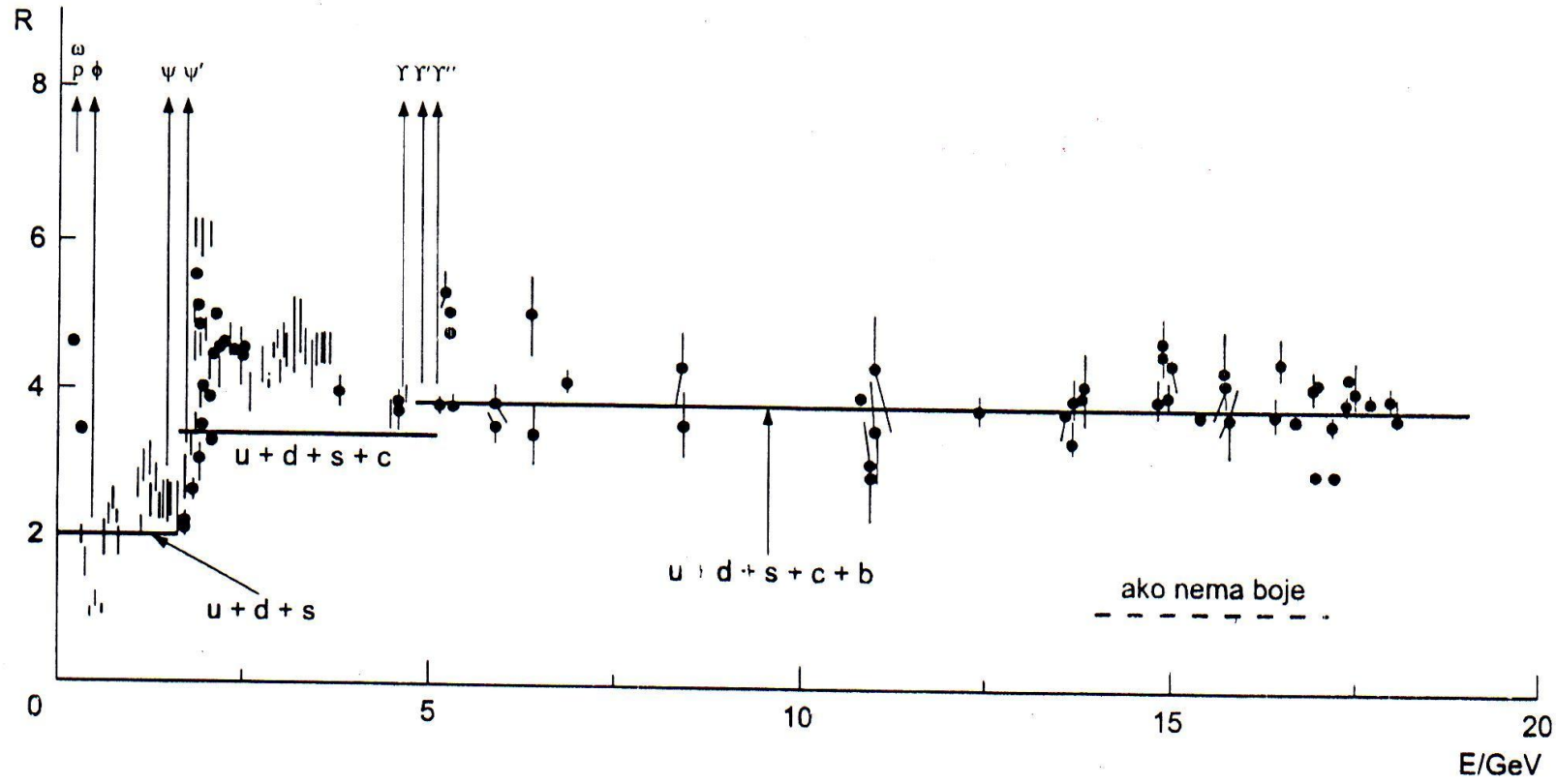
$$\sigma(e^+e^- \to \text{hadrons}) = 3\sum_{u,d,s,..}\frac{4\pi\alpha^2}{3s}Q_q^2$$

Factor 3 comes from colours

- Usual to express as ratio compared to $\sigma(e^+e^- \to \mu^+\mu^-)$

$$R_\mu = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3\sum_{u,d,s,..}Q_q^2$$

Omjer R – pragovi produkcije i OTKRIĆE NOVIH STUPNJEVA SLOBODE (boja i novi okusi)



ČAROBNI OKUS u slijedu uspostavljanja simetrije KVARKOVA i LEPTONA

- ZEMALJSKA TVAR
- ETERIČNA (STRANA)
  1937 mion
  1947 stranost
- ČAROBNI OKUS
  (Niu, Mikumo, Maeda'71
-Kobayashi&Maskawa'74)

.. OKUS LJEPOTE ..

$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$

$\begin{pmatrix} \mu^- \\ \end{pmatrix}$

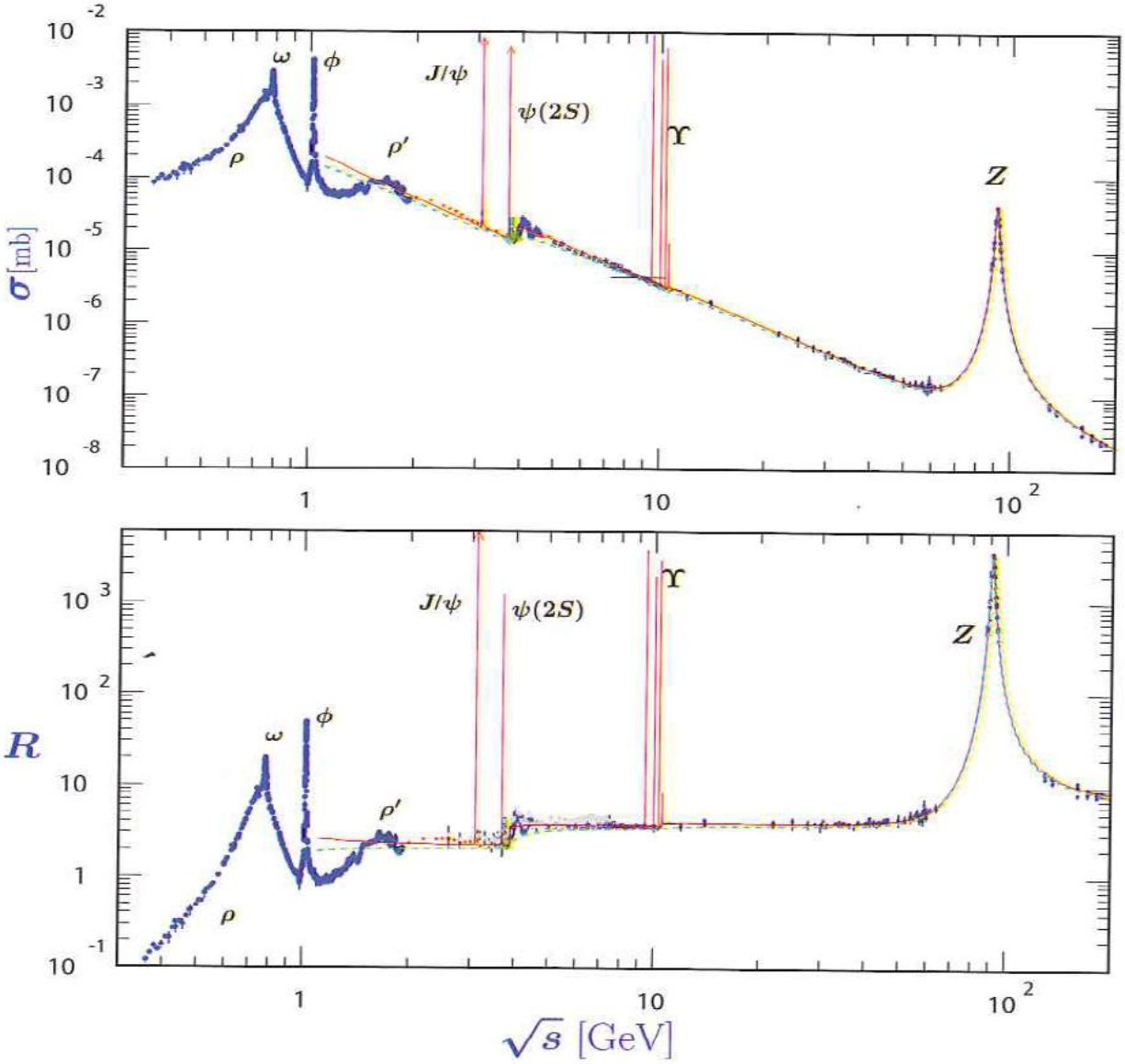
$\begin{pmatrix} c \\ s \end{pmatrix}$ "c" :

Sam Thing $p + Be \to e^+e^- + X$

Burton Richter e^+e^- (SLAC) J/ψ

$\begin{pmatrix} b \\ \end{pmatrix} \begin{pmatrix} \tau^- \\ \end{pmatrix}$

UDARNI PRESJEK & R



NOVEMBARSKA REVOLUCIJA '74

- Iza lažnog linearnog porasta R-a su dvije uske rezonance na 3.1 & 3.695, širine 0.06 & 0.2 MeV – skrivena čar QCD-a prema Appelquistu i Politzeru

$$J/\psi\,(1^3S_1) \quad \& \quad \psi'(2^3S_1)$$

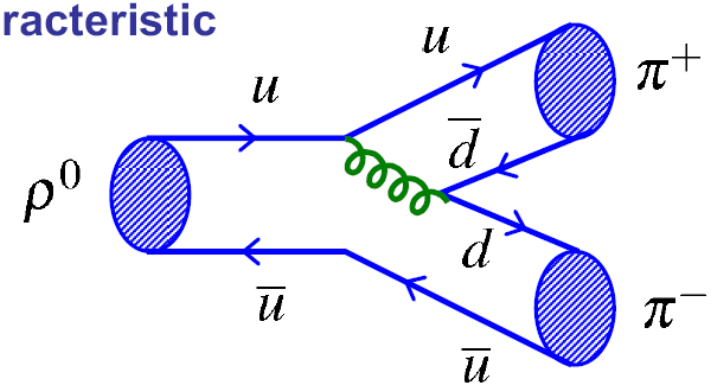
- Ustaljenje pokusa na R = 10/3 + 1 -- -"tau lepton" na 1.77 GeV (Perl 1975)
- Spektroskopija čarobnih hadrona po otkriću Golhaberove grupe D^0, D^+

Wide resonance implies short lifetime
(see part II or later discussion of Z)

$$\tau = \frac{\hbar}{\Gamma}$$

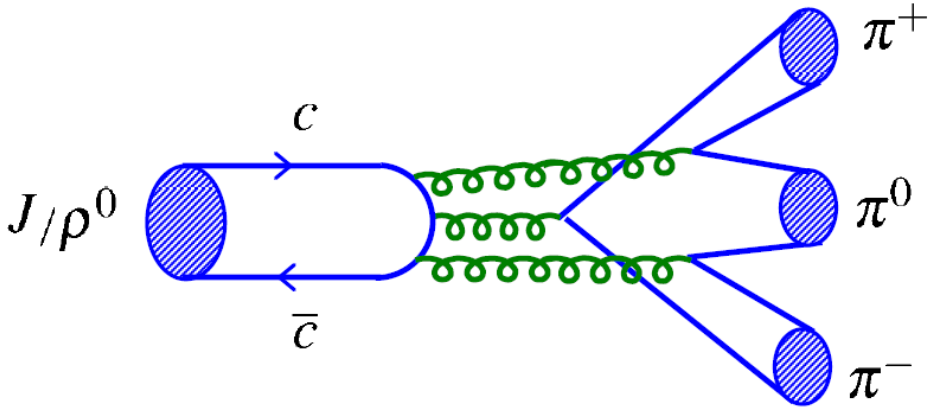
e.g. $\Gamma_\rho = 146\,\mathrm{MeV} \rightarrow \tau_\rho = 4.5 \times 10^{-24} s$

Very short lifetimes are characteristic of strong decays



Narrower resonances characteristic of suppressed strong decays

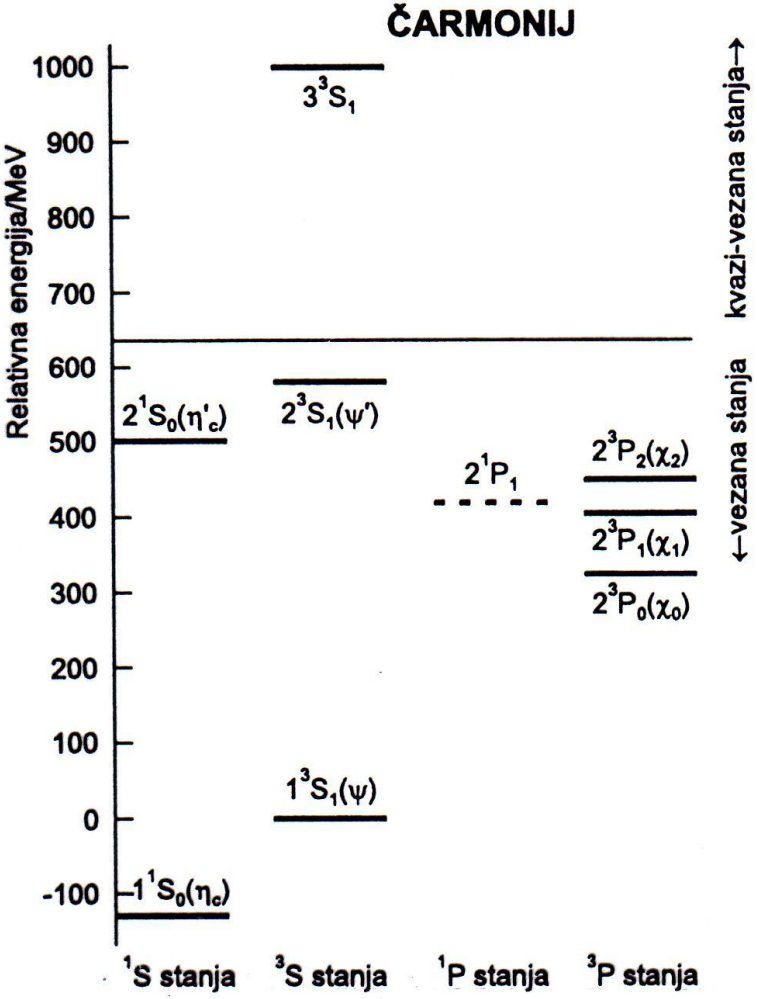
e.g. $\Gamma_{J/\psi} = 94\,\mathrm{keV} \rightarrow \tau_{J/\psi} = 7.0 \times 10^{-21}\, s$

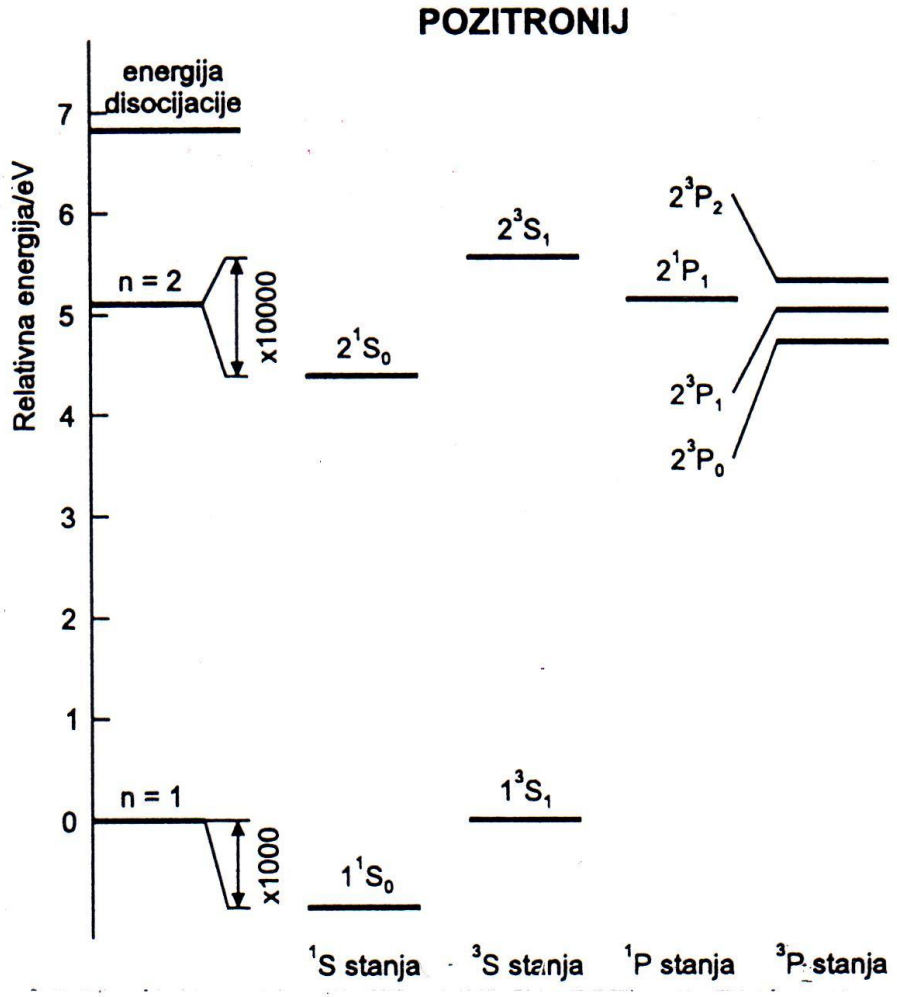


ZWEIG Suppression

No decay to $D^+(c\bar{d})D^-(d\bar{c})$

since $m_{J/\psi} < 2m_{D^\pm}$


ČARMONIJ
Relativna energija/MeV
1000
900
800
700
600
500
400
300
200
100
0
-100
3^3S_1
$2^1S_0(\eta'_c)$
$2^3S_1(\psi')$
2^1P_1
$2^3P_2(\chi_2)$
$2^3P_1(\chi_1)$
$2^3P_0(\chi_0)$
$1^3S_1(\psi)$
$1^1S_0(\eta_c)$
←vezana stanja kvazi-vezana stanja→
^1S stanja
^3S stanja
^1P stanja
^3P stanja


POZITRONIJ
Relativna energija/eV
energija disocijacije
7
6
5
4
3
2
1
0
n = 2
x10000
n = 1
x1000
2^1S_0
1^1S_0
2^3S_1
1^3S_1
2^3P_2
2^1P_1
2^3P_1
2^3P_0
^1S stanja
^3S stanja
^1P stanja
^3P stanja

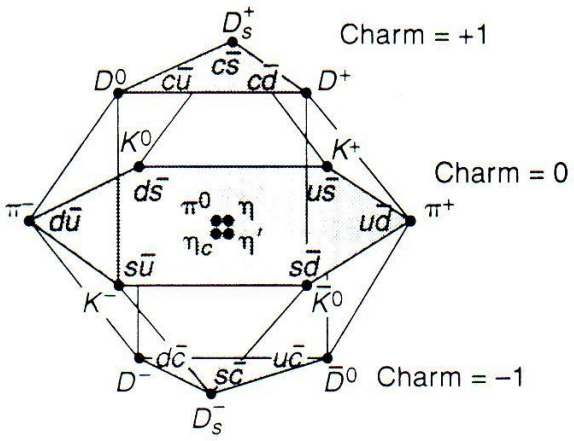
SPEKTRO-SKOPIJA ČAROBNIH STANJA

SU(4)

15-plet mezona

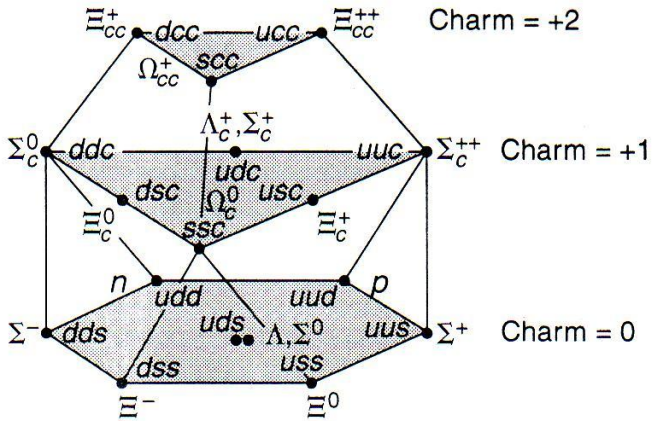
20-plet bariona

FEČ, str. 192



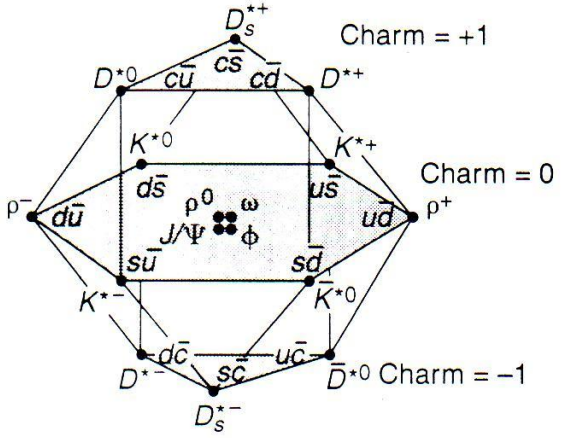
0⁻ Mesons

(a)



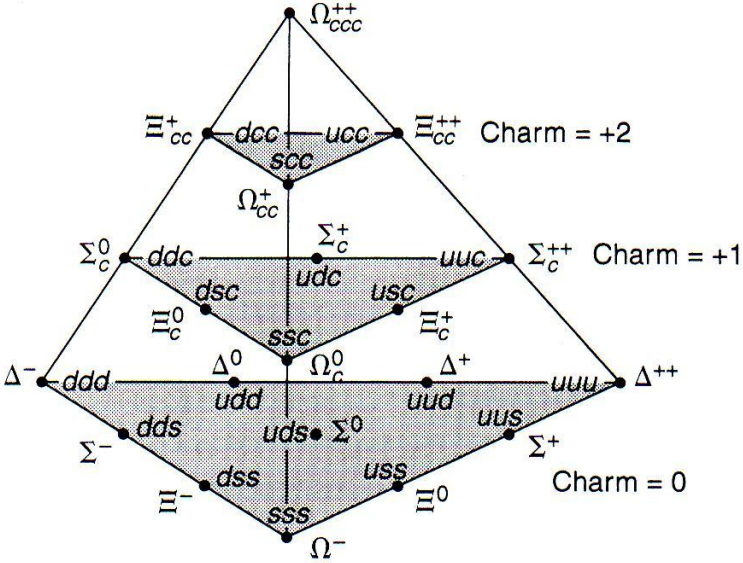
$\frac{1}{2}^+$ Baryons

(c)



1⁻ Mesons

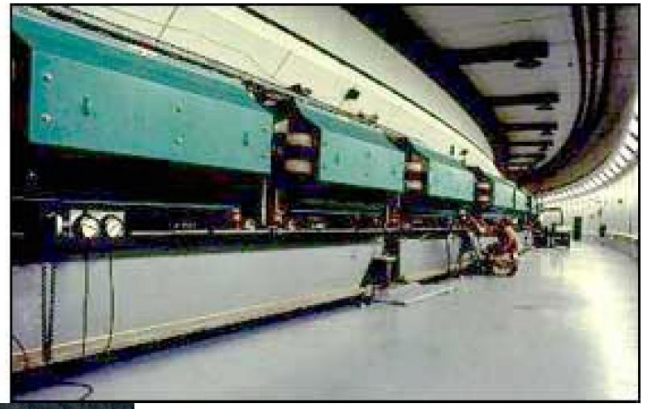
(b)



$\frac{3}{2}^+$ Baryons

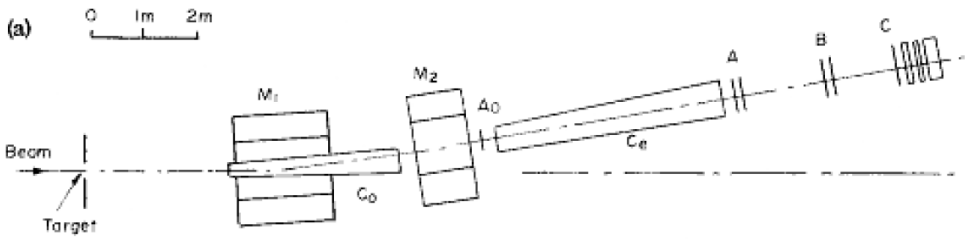
(d)

Brookhaven National Lab
Alternating Gradient Synchrotron



The Process: p + Be → e^+ e^- X

very narrow width
⇒ long lifetime



at BNL AGS

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen
J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technolog
Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \rightarrow e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

This experiment is part of a large program to daily with a thin Al foil. The beam spot

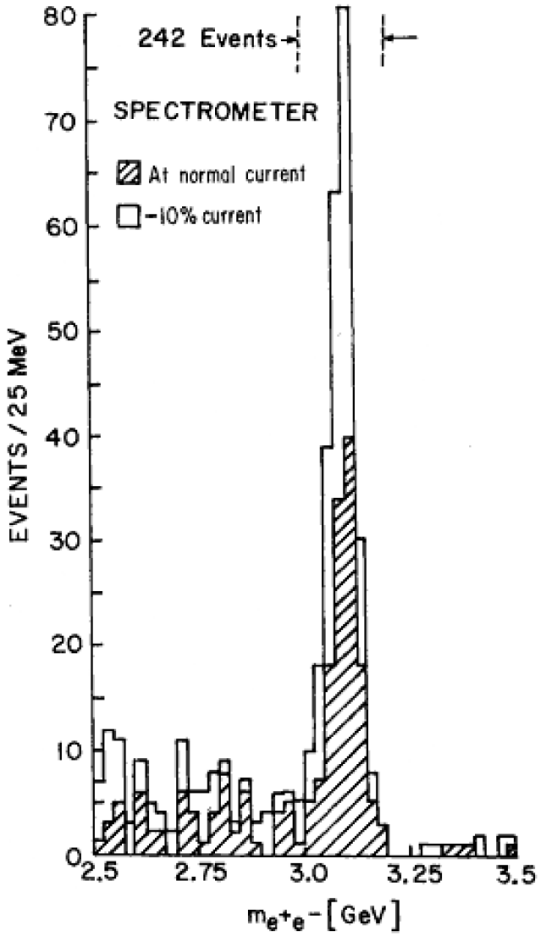
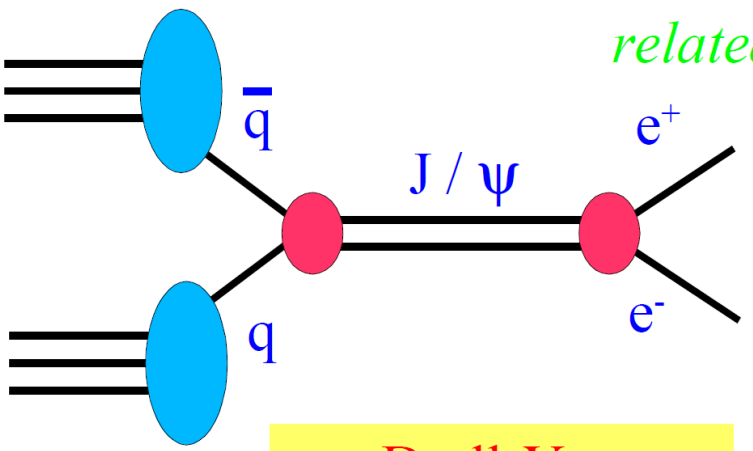
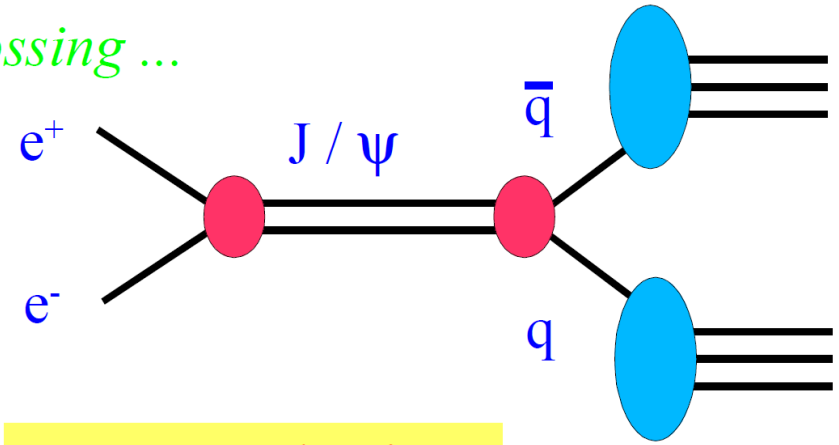


FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

related by crossing ...





Drell-Yan
Brookhaven AGS

e^+e^- Production
SLAC SPEAR
Frascati ADONE

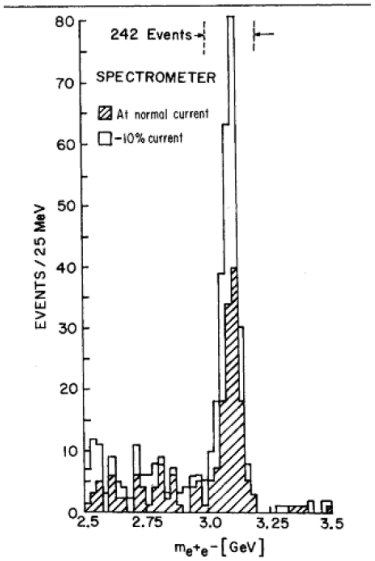
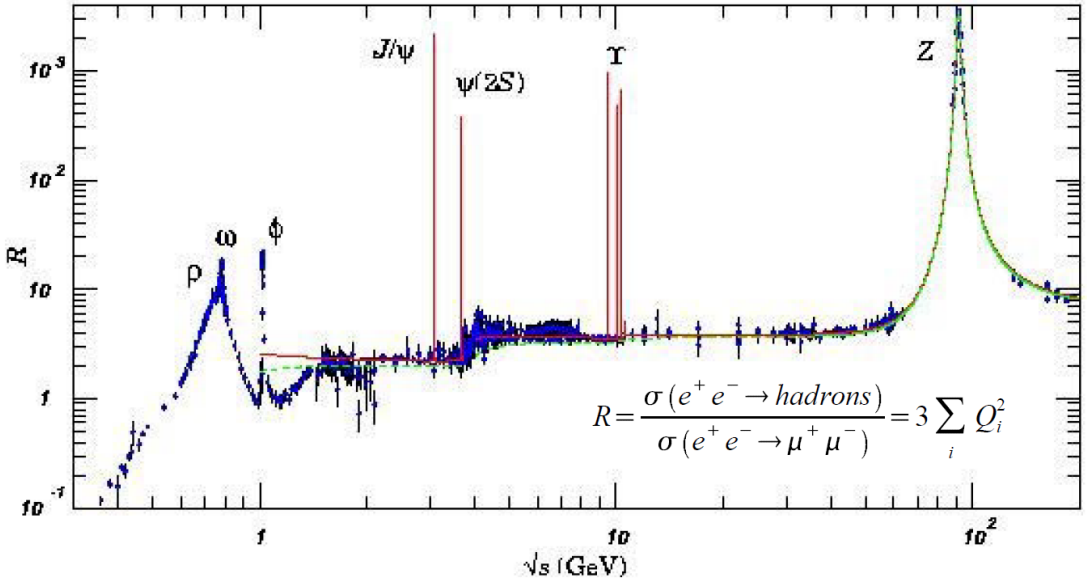
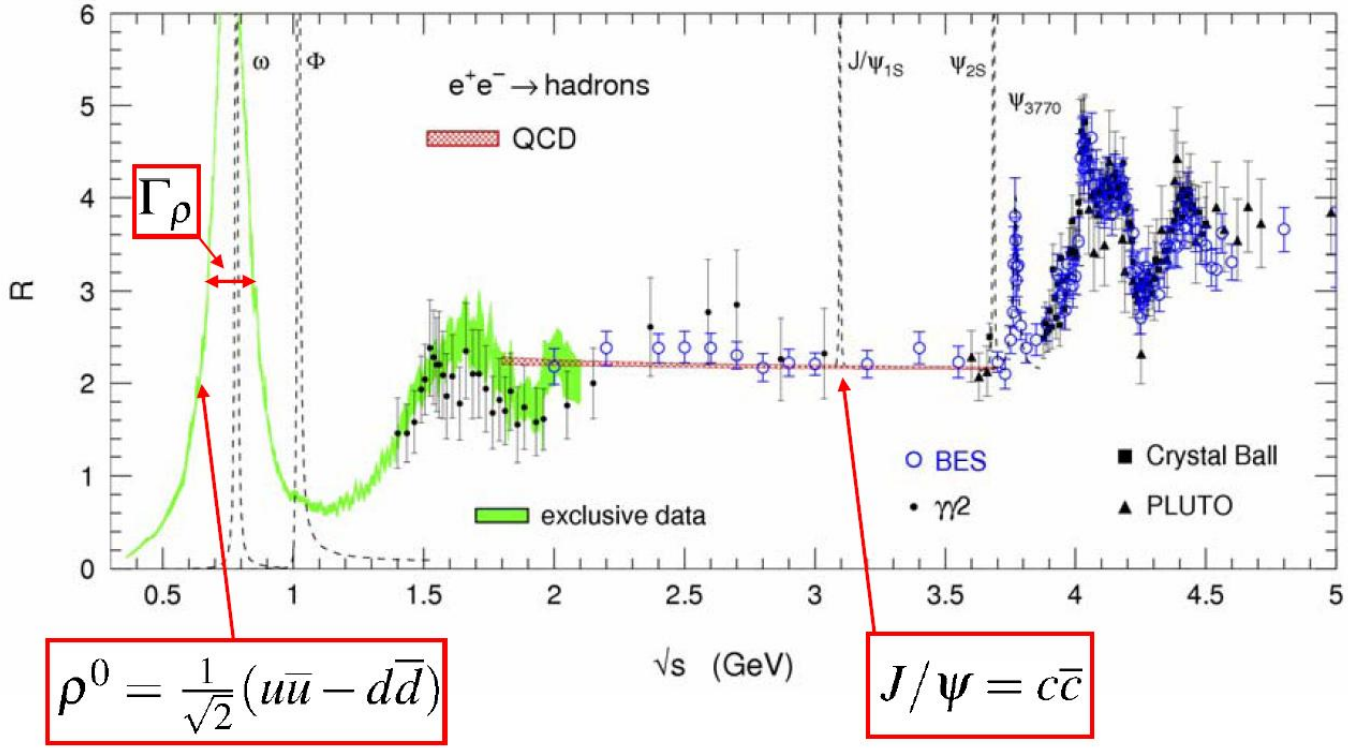


FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

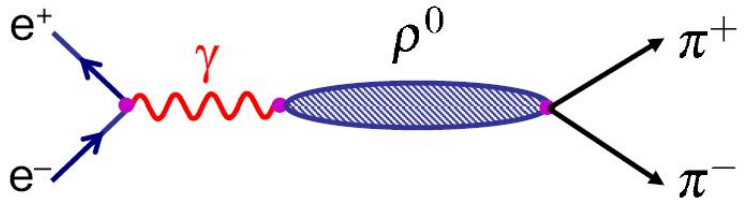


NISKOENERGIJSKE REZONANTNE PRODUKCIJE

- Low energy region complicated by resonant production of decaying meson states



e.g.



FWHM Width of resonance:

$$\Gamma_\rho = 146\,\mathrm{MeV}$$

- **SKRIVENA LJEPOTA '77 - Ledermanova grupa na Fermilabu - "upsilon" najprije u reakciji**

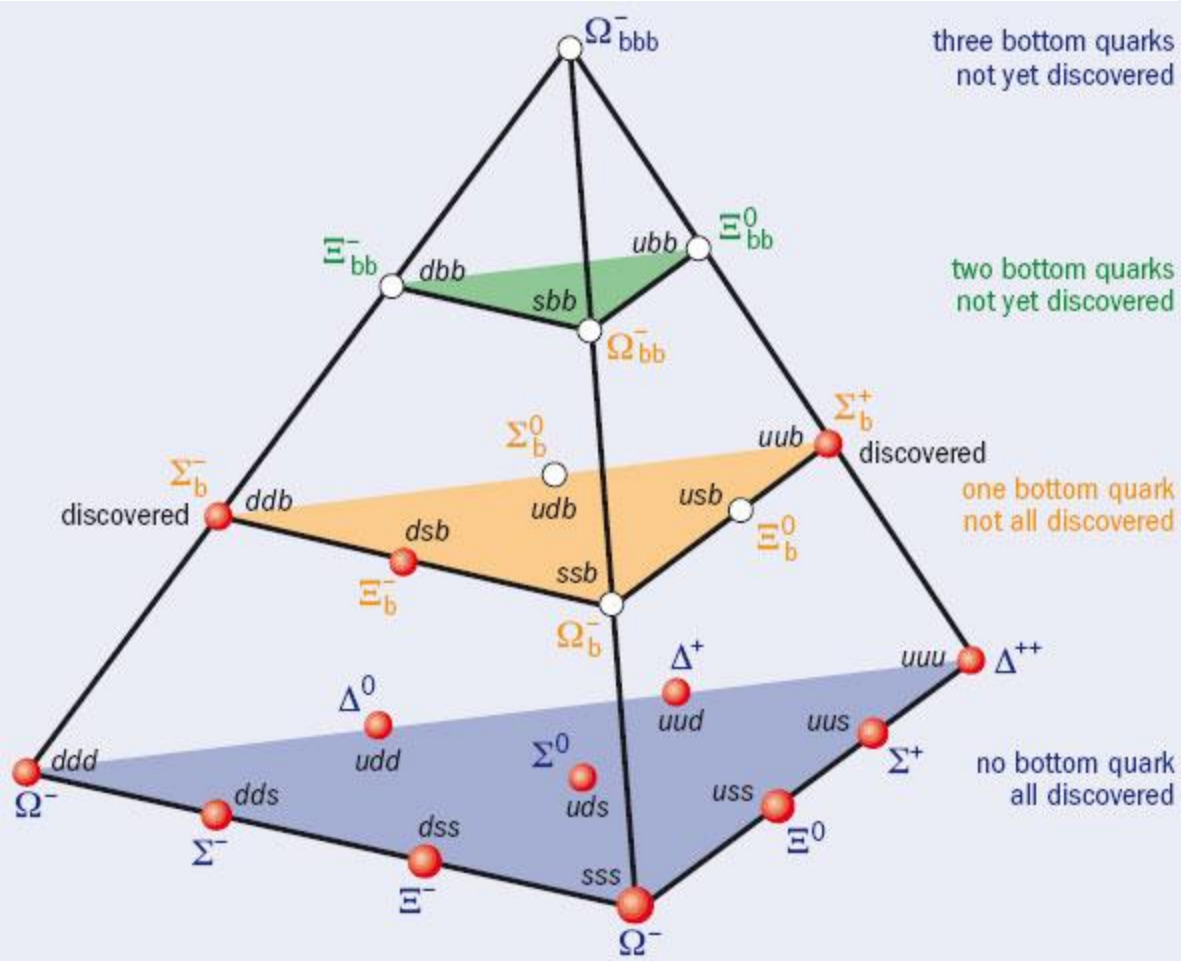
$$p + (Cu, Pt) \rightarrow \mu^+\mu^- + X$$

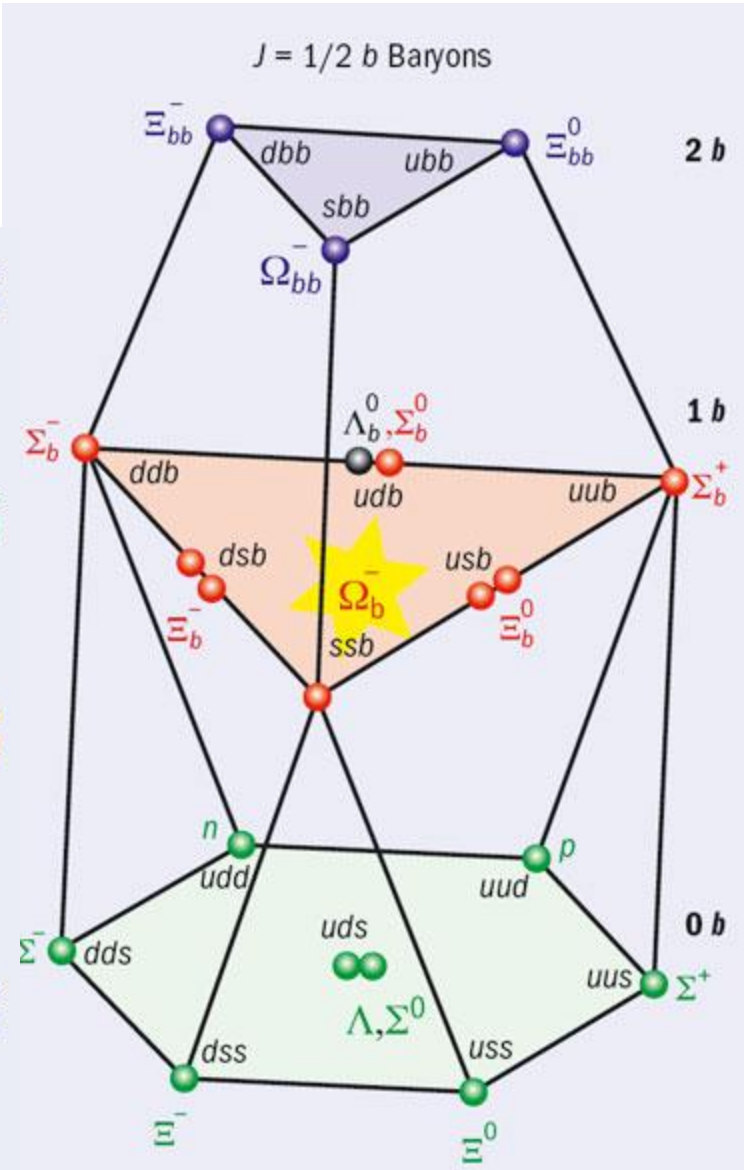
$$\Upsilon(9.4)\ ,\ \Upsilon'(10)\ ,\ \Upsilon''(10.4)\quad GeV$$

- **Spektroskopija "hadrona ljepote" po otkriću B-mezona "otkrivene ljepote (Cornell 1980)**

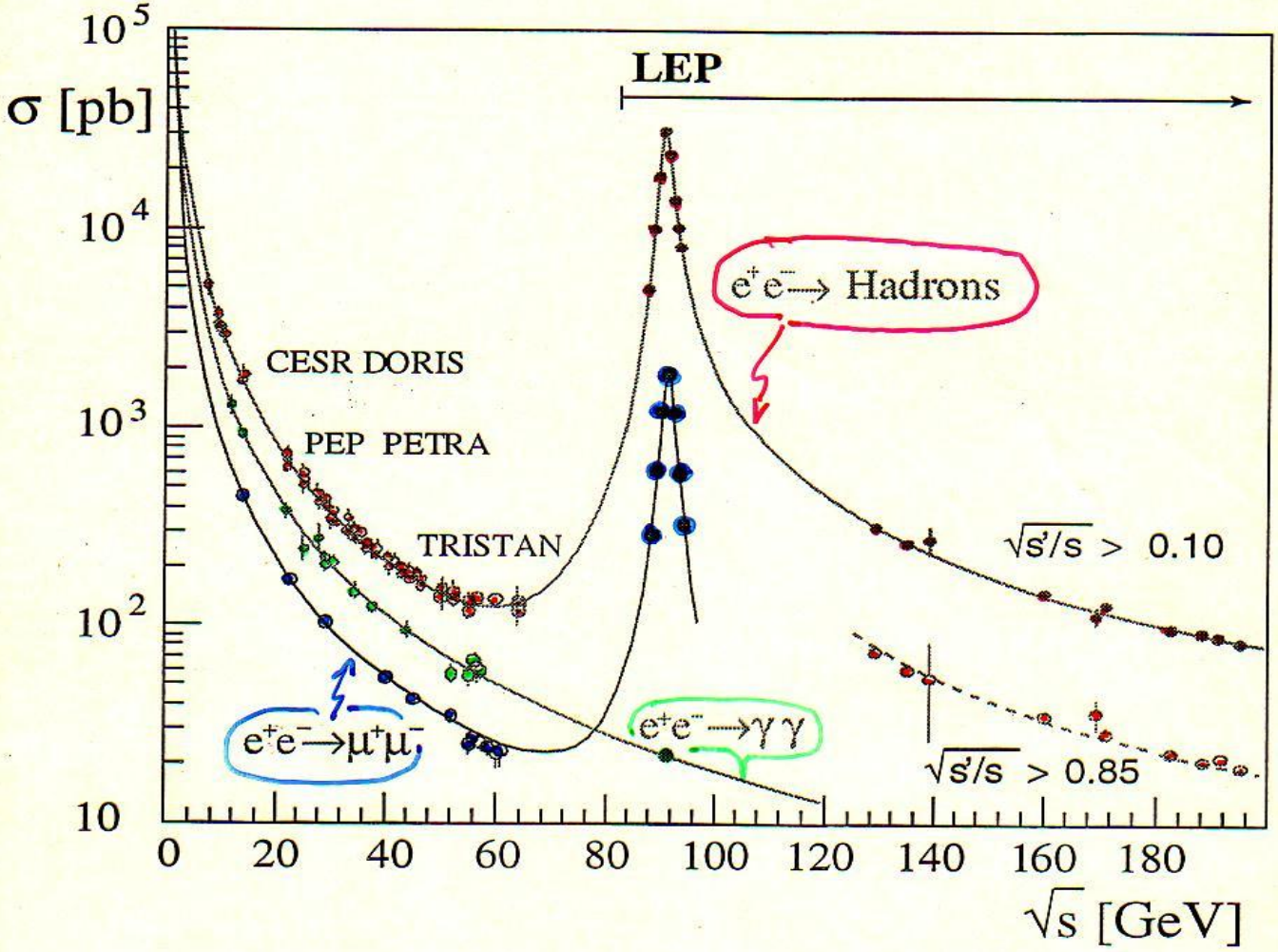
- **Nova epizoda – testovi preciznosti na Z-rezonanci na LEP-u**

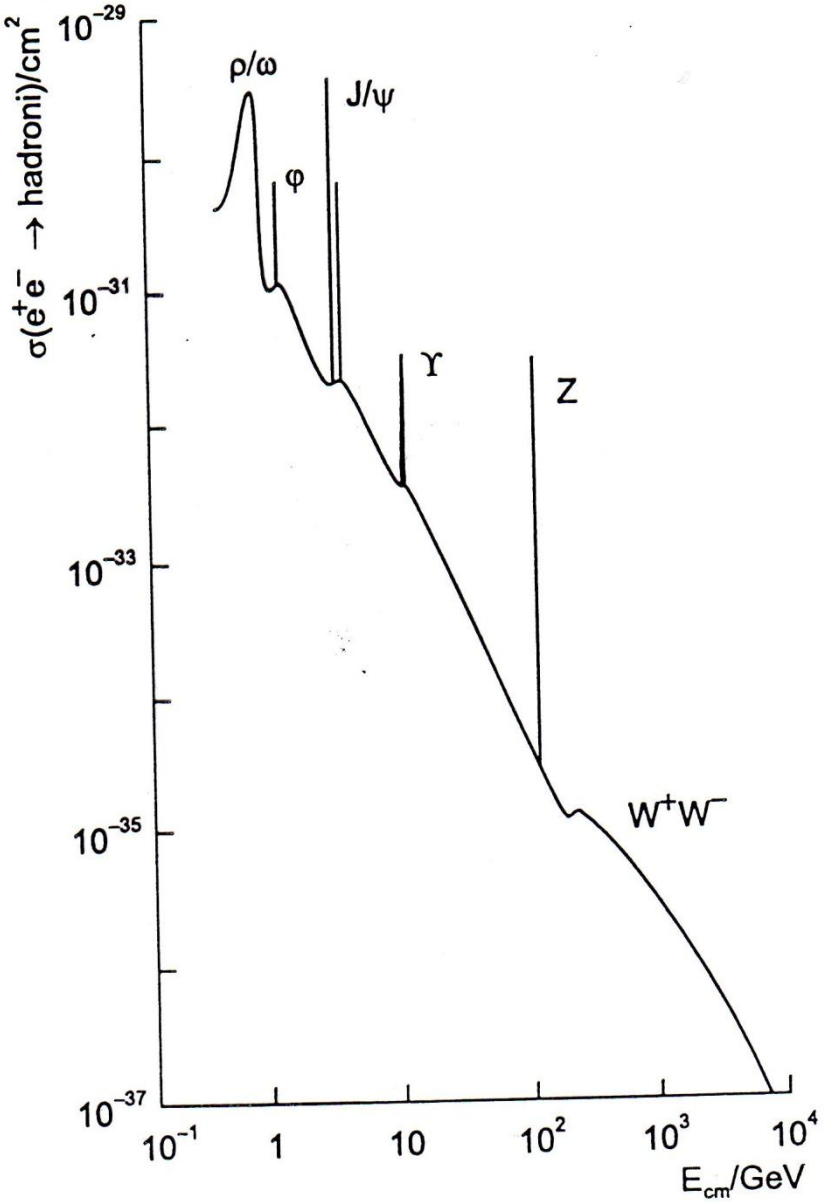
Omega_b


three bottom quarks
not yet discovered
two bottom quarks
not yet discovered
discovered
one bottom quark
not all discovered
no bottom quark
all discovered
ddd
dds
dss
sss
udd
uds
uus
uss
uuu
ddb
dsb
ssb
udb
usb
uub
dbb
sbb
ubb


J = 1/2 b Baryons
2 b
1 b
0 b
dbb
ubb
sbb
ddb
udb
uub
dsb
usb
ssb
n
p
udd
uud
uds
dds
uus
dss
uss

e^+e^- Annihilations at LEP




$\sigma(e^+e^- \to \text{hadroni})/\text{cm}^2$
10^{-29}
10^{-31}
10^{-33}
10^{-35}
10^{-37}
ρ/ω
φ
J/ψ
ϒ
Z
W^+W^-
10^{-1}
1
10
10^2
10^3
10^4
E_{cm}/GeV

1974: The J/Psi (charm) discovery $p+N \rightarrow J/\psi$

... 1976 Nobel Prize

1977: The Upsilon (bottom) discovery $p+N \rightarrow \Upsilon$

1983: The W and Z discovery $p + \overline{p} \rightarrow W/Z$

... 1984 Nobel Prize

PROIZVODNJA HADRONSKIH MLAZOVA

Quarks and gluons are not free observable particles. Partons fragment into a collimated stream of hadrons:

- 2 jet event: $e^+ + e^- \rightarrow q + \bar{q}$
- 3 jet event: $e^+ + e^- \rightarrow q + \bar{q} + g$

Note: Fragmentation is a long-range and thus non-perturbative process. Various models have been developed to describe in a Monte-Carlo simulation the formation of jets, e.g. PYTHIA (color-dipole model)!

The distribution of hadrons is described by a fragmentation function of a hadron h with respect to a quark q: $D_q^h(z)$

z: longitudinal momentum fraction of hadrons in direction of quark q

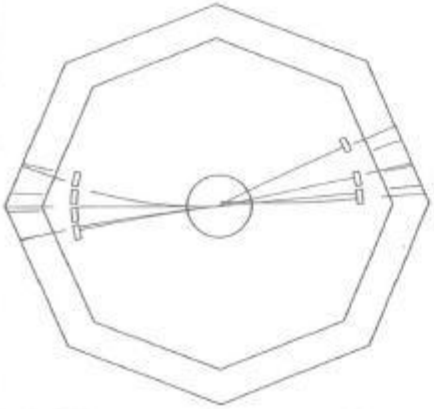
$$z = \frac{\vec{p}_h \cdot \vec{p}}{|\vec{p}|^2}$$

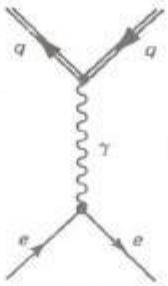
$D_q^h(z)dz$ → Probability to find hadron h with momentum fraction z and z+dz

Fragmentation functions have to be extracted from data!

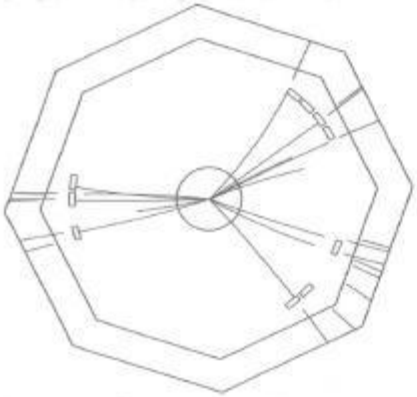
OTKRIĆE 3. MLAZA OTVARA PUT KVANTNOJ KROMODINAMICI

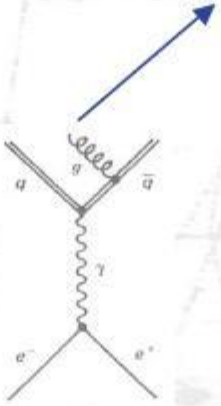
2 jet events





3 jet events





Gluon radiation gives rise to 3rd jet!

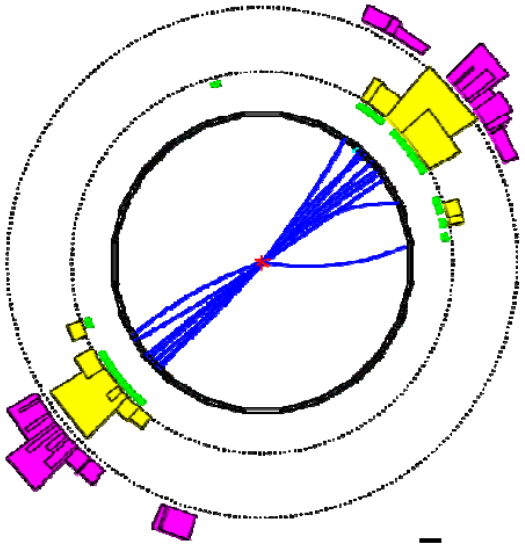
Experimental evidence for gluons: DESY laboratory at PETRA, 1979

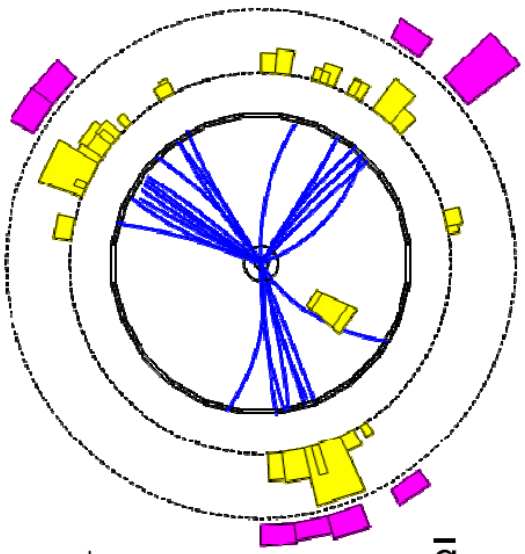
PRODUKCIJE GLUONA

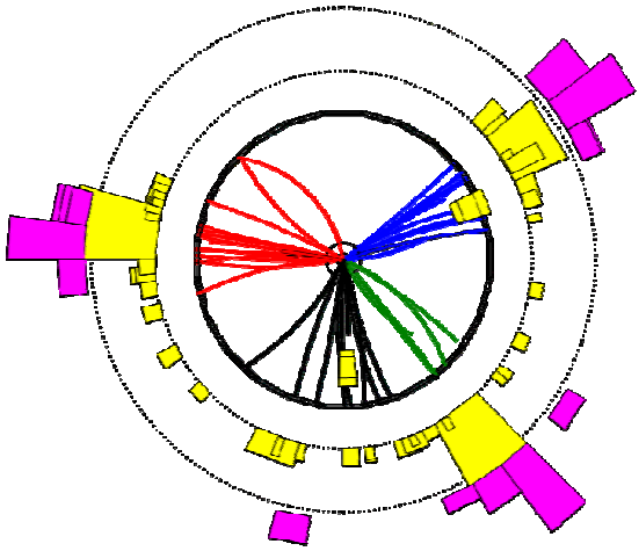
★ e^+e^- colliders are also a good place to study gluons

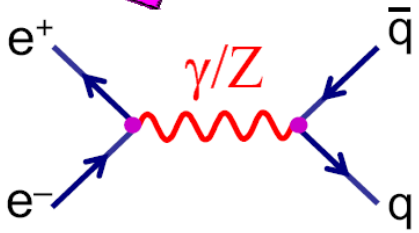
$e^+e^- \to q\bar{q} \to 2\text{jets}$ $e^+e^- \to q\bar{q}g \to 3\text{jets}$ $e^+e^- \to q\bar{q}gg \to 4\text{jets}$

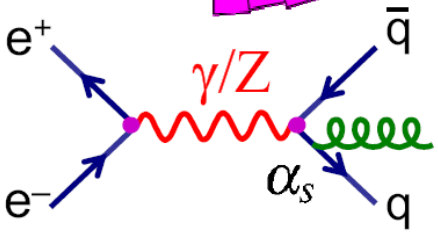
OPAL at LEP (1989-2000)

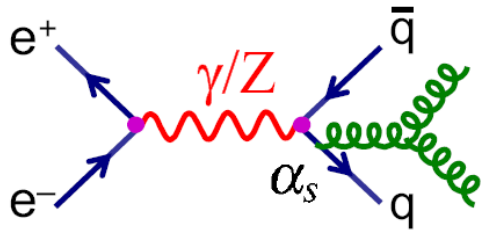








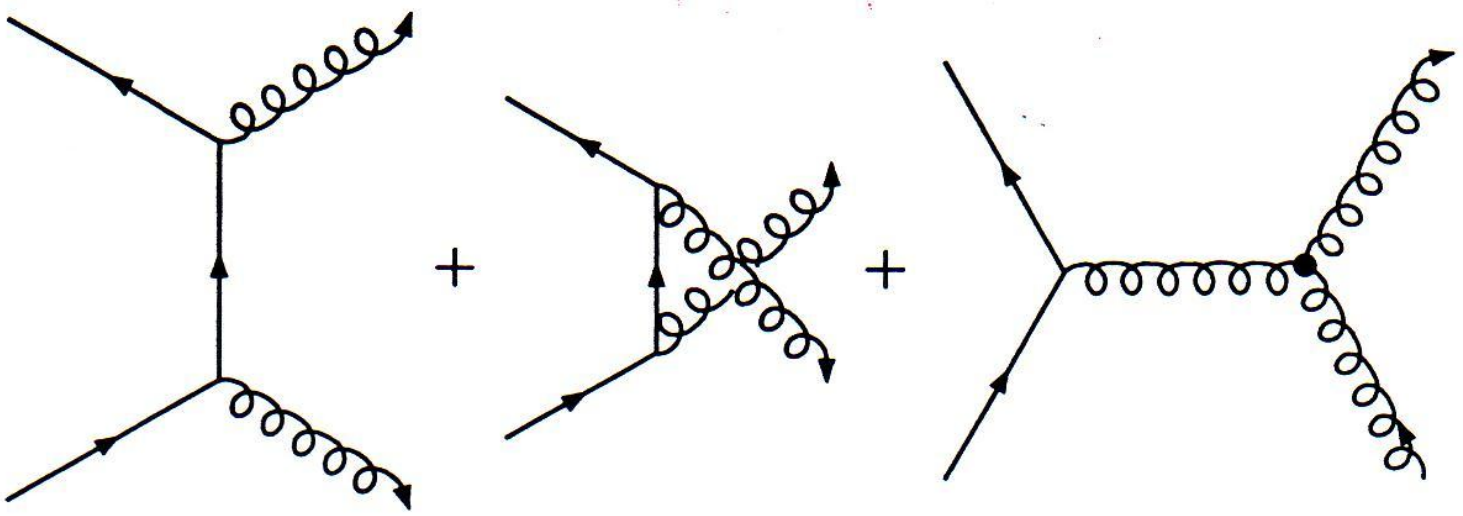




Experimentally:

- Three jet rate ➡ measurement of α_s
- Angular distributions ➡ gluons are spin-1
- Four-jet rate and distributions ➡ QCD has an underlying SU(3) symmetry

GLUONSKE SAMOINTERAKCIJE SU(3)-boje



Slika 4.27: Dodatno trogluonsko vezanje koje se pojavljuje u komptonskoj amplitudi kromodinamike

JAKOST GLUONSKOG VEZANJA